2

Radionavigation System User Requirements

The requirements of civil and military users for radionavigation services are based upon the technical and operational performance needed for military missions, transportation safety, and economic efficiency. For civil users, and for military users in missions similar to civil users (e.g., en route navigation), the requirements are defined in terms of discrete “phases of navigation.” These phases are categorized primarily by the characteristics of the navigational problem as the mobile craft passes through different regions in its voyage. For example, the ship navigational problem becomes progressively more complex and risky as the large ship passes from the high seas, into the coastal area, and finally through the harbor approach and to its mooring. Thus, it is convenient to view each segment separately for purposes of analysis.

Unique military missions and national security needs impose a different set of requirements which cannot be viewed in the same light. Rather, the requirements for military users are more a function of the system’s ability to provide services that equal or exceed tactical or strategic mission requirements at all times in relevant geographic areas, irrespective of hostile enemy action.

In the discussion that follows, both sets of requirements (civil and military) are presented in a common format of technical performance characteristics whenever possible. These same characteristics are used to define radionavigation system performance in Section 3.

2.1 Phases of Navigation

Each mode of transportation has various phases with different requirements to provide safe and cost-effective operation during each phase.

2.1.1 Air

The two basic phases of air navigation are en route/terminal and approach/landing.

A. En Route/Terminal

The en route/terminal phase includes all portions of flight except that within the approach/landing phase. It contains four subphases which are categorized by differing geographic areas and operating environments as follows:

1. Oceanic En Route: This subphase covers operations over ocean areas generally characterized by low traffic density and no independent surveillance coverage.
2. Domestic En Route (High Altitude and Low Altitude Routes): Operations in this subphase are typically characterized by moderate to high traffic densities. This necessitates narrower route widths than in the oceanic en route subphase. Independent surveillance is generally available to assist in ground monitoring of aircraft position.
3. Terminal Area: Operation in the terminal area is typically characterized by moderate to high traffic densities, converging routes, and transitions in flight altitudes. Narrow route widths are required. Independent surveillance is generally available to assist in ground monitoring of aircraft position.
4. Remote Areas: Remote areas are special geographic or environmental areas characterized by low traffic density and terrain where it has been difficult to cost-effectively implement comprehensive navigation coverage. Typical of remote areas are mountainous terrain, offshore areas, and large portions of the state of Alaska.

B. Approach/Landing

The approach/landing phase is that portion of flight conducted immediately prior to touchdown. It is generally conducted within 10 nautical miles (nm) of the runway. Two subphases may be classified as nonprecision approach and precision approach and landing.

2.1.2 Marine

Marine navigation in the U.S. consists of four major phases identified as inland waterway, harbor/harbor approach, coastal, and ocean navigation. Standards or requirements for safety of navigation and reasonable economic efficiency can be developed around these four phases. Specialized requirements, which may be generated by the specific activity of a ship, must be addressed separately.

A. Inland Waterway

Inland waterway navigation is conducted in restricted areas similar to those for harbor/harbor approach. However, in the inland waterway case, the focus is on nonseagoing ships and their requirements on long voyages in restricted waterways, typified by tows and barges in the U.S. Western Rivers System and the U.S. Intracoastal Waterway System.

In some areas, seagoing craft in the harbor phase of navigation and inland craft in the inland waterway phase share the use of the same restricted waterway. The distinction between the two phases depends primarily on the type of craft. It is made because seagoing ships and typical craft used in inland commerce have differences in physical characteristics, personnel, and equipment. These differences have a significant impact upon their requirements for aids to navigation. Recreational and other relatively small craft are found in large numbers in waters used by both seagoing and inland commercial traffic and generally have less rigid requirements in either case.

B. Harbor/Harbor Approach

Harbor/harbor approach navigation is conducted in waters inland from those of the coastal phase. For a ship entering from the sea or the open waters of the Great Lakes, the harbor approach phase begins generally with a transition zone between the relatively unrestricted waters where the navigational requirements of coastal navigation apply, and narrowly restricted waters near and/or within the entrance to a bay, river, or harbor, where the navigator enters the harbor phase of navigation. Usually, the harbor phase requires navigation of a well-defined channel which, at the seaward end, is typically from 180 to 600 meters in width if it is used by large ships, but may narrow to as little as 120 meters farther inland. Channels used by smaller craft may be as narrow as 30 meters.

From the viewpoint of establishing standards or requirements for safety of navigation and promotion of economic efficiency, there is some generic commonality between the harbor and harbor approach phases. In each case, the nature of the waterway, the physical characteristics of the vessel, the need for frequent maneuvering of the vessel to avoid collision, and the closer proximity to grounding danger impose more stringent requirements for accuracy and for real-time guidance information than for the coastal phase.

For analytical purposes, the phases of harbor approach and harbor navigation are built around the problems of precise navigation of large seagoing and Great Lakes ships in narrow channels between the transition zone and the intended mooring.

C. Coastal Navigation

Coastal navigation is that phase in which a ship is within 50 nm from shore or the limit of the continental shelf (200 meters in depth), whichever is greater, where a safe path of water at least one mile wide, if a one-way path, or two miles wide, if a two-way path, is available. In this phase, a ship is in waters contiguous to major land masses or island groups where transoceanic traffic patterns tend to converge in approaching destination areas; where interport traffic exists in patterns that are essentially parallel to coastlines; and within which ships of lesser range usually confine their operations. Traffic-routing systems and scientific or industrial activity on the continental shelf are encountered frequently in this phase of navigation. Ships on the open waters of the Great Lakes also are considered to be in the coastal phase of navigation.

The boundary between coastal and ocean navigation is defined by one of the following which is farthest from land:

- 50 nautical miles from land.
- The outer limit of offshore shoals, or other hazards on the continental shelf.
- Other waters where traffic separation schemes have been established, and where requirements for the accuracy of navigation are thereby made more rigid than the safety requirements for ocean navigation.

D. Ocean Navigation

Ocean navigation is that phase in which a ship is beyond the continental shelf (200 meters in depth), and more than 50 nm from land, in waters where position fixing by visual reference to land or to fixed or floating aids to navigation is not practical. Ocean navigation is sufficiently far from land masses so that the hazards of shallow water and of collision are comparatively small.

2.1.3 Land

In comparison with the air and marine communities, there are no well-defined phases of land navigation; however, there are different applications with unique accuracy requirements. The land navigation applications fall into four basic categories; highways, transit, rail, and non-transportation uses. Ongoing work on Intelligent Transportation Systems (ITS), which includes R&D and operational test programs using radionavigation that are wholly or partially funded by the Department of Transportation’s modal administrations (including FHWA, FTA, and NHTSA), will be used to clarify and validate user requirements.

A. Highways

Radionavigation techniques in highway applications are used individually or are integrated with vehicle-to-roadside communications and map-matching techniques to provide various user services. Some in-vehicle systems using radionavigation techniques are under development, some are being used in operational tests, and some are currently in use. Examples of systems in development include augmentation of GPS vehicle location data by providing DGPS correction values over wireless communications. Also under development is a system for vehicle location monitoring using GPS integrated with wireless packet data systems. Planned operational tests for ITS funded by FHWA include the use of radionavigation for automated vehicle location for mayday response, route guidance, mass transit scheduling, and mileage determination. Systems in use include radionavigation for dispatching roadside assistance vehicles and automated location tracking and scheduling of commercial vehicles. Radionavigation is used by various highway departments for asset management by using GPS coordinates to identify, for example, locations of bridges, highway signs, and overpasses. Table 2-1 shows examples of ITS user services requiring the use of radionavigation. A full description of all of the ITS user services can be found in Appendix A.

B. Transit

Transit systems also benefit from the same radiolocation-based technologies used for highways. Automated vehicle location techniques assist in fleet management, scheduling, real-time customer information, and emergency assistance. Also, services such as automated transit stop annunciation are being investigated. There are several operational tests being funded by FTA to explore uses of radionavigation in transit systems for functions such as scheduling, automated dispatch, vehicle tracking, and traffic signal pre-emption.

C. Rail

The railroad industry may benefit from the use of radionavigation systems to aid in train location determination, monitoring, scheduling and management. These systems also have the potential for use in collision avoidance applications.

D. Non-Transportation Uses

Examples of non-transportation-based applications of radionavigation include meteorology; mapping, charting, geodesy, and surveying; precise timing; development of geographic information systems; and recreation uses. Surveying applications encompass densification control, corridor and project control, mapping control, structure control, cadastral surveys, and airborne GPS photogeometry control. The development of hand-held GPS receivers accompanied by declining prices is also opening markets for recreational uses such as hiking and backpacking.

Table 2-1. ITS User Services Requiring Use of Radionavigation

Travel and Traffic Management
Pre-Trip Travel Information
En Route Driver Information
Route Guidance
Incident Management
Travel Demand Management
Public Transportation Management
Public Transportation Management
Personalized Public Transportation
Commercial Vehicle Operations
Commercial Fleet Management
Emergency Management
Emergency Vehicle Management
Emergency Notification and Personal Security
Advanced Vehicle Safety Systems
Intersection Collision Avoidance

In general, geodesy and surveying have not been considered phases of navigation, but have provided the coordinate frames within which navigation is performed.

More recently, however, geodetic surveying methods have been used for position determination while in motion on land. As an example, one can profile an airport using kinematic DGPS on-the-fly methodology and obtain centimeter-accuracy profiles. This is an example of precise positioning while moving and not necessarily navigation in the full sense. Precision highway inventory management could be included as well.

Precise land navigation is in the development phase. A specific example of this might be agriculture. The exact trajectory of a tractor would be preprogrammed to plow, plant, fertilize, or harvest at the subdecimeter (or better) level. Certain pit-mining operations, heavy equipment operations such as excavating or bulldozing, and other possibilities such as highway equipment robotics fit this description.

The above examples are ones requiring centimeter accuracy navigation or positioning. There are many other land navigation activities which require decimeter to few-meter accuracy. The utility services might want to locate an underground main; a rancher may want to mark problem locations and return by way of waypoint navigation; a police investigator may want to mark and return to an accident site; and a search and rescue unit might want to drive by land vehicle or hike to a distress victim.

2.1.4 Space

For Earth-orbiting space activities, the mission phases can be generally categorized as the ground launch phase, the on-orbit phase, and the reentry and landing phase. In addition to the government sponsored space activities coordinated by NASA, there is a growing U.S. commercial space transportation industry seeking to launch both government and private payloads. There is also a growing private sector presence in space commerce that reflects sizable investments in such emerging uses as materials processing, land mobile services, radiodetermination, and remote sensing.

A. Ground Launch Phase

This phase is defined as that portion of the mission from the point at which a vehicle leaves the launch pad to the point wherein the vehicle inserts the payload into Earth orbit.

B. On-Orbit Phase

This is the phase wherein key operations or data gathering from an experiment to meet the primary mission objectives is performed. During this phase, the launch vehicle may deploy a satellite or perform positional maneuvers in support of onboard experiments. Vehicles capable of reentry may also retrieve a satellite for return to Earth. This phase essentially ends when the vehicle has completed its mission or initiates de-orbit maneuvers. In this phase, free-flying spacecraft perform their experiments and operations in their required orbits. In those cases where the spacecraft will not be returned to Earth, this operational phase continues until such time as the spacecraft is shut down or can no longer perform its functions. For those spacecraft to be returned to Earth, this phase essentially ends when the spacecraft is either retrieved by a reentry vehicle or returns to Earth on its own.

C. Reentry and Landing Phase

This phase begins when a reentry vehicle, possibly with onboard experiments or a retrieved spacecraft, initiates de-orbit maneuvers. The vehicle goes through atmospheric entry and makes an unpowered landing. This phase ends when the vehicle comes to a full stop.

2.2 Civil Radionavigation System Requirements

The radionavigation requirements of civil users are determined by a DOT process which begins with acknowledgment of a need for service in an area or for a class of users. This need is normally identified in public safety and cost/benefit need analysis generated internally, from other Federal agencies, from the user public, or as required by Congress. User conferences have highlighted land user needs not previously defined.

Radionavigation services provide civil users with the following:

- Service adequate for safety.
- Economic performance/benefit enhancement.
- Support of an unlimited number of users.
- Continuous availability for fix information.

Radionavigation system replacement candidates must be subjected to a total system analysis in terms of safety and economic performance. This involves the evaluation of a number of complex factors. Replacement decisions will not be made on the basis of a simple comparison of one performance characteristic such as system accuracy.

It must also be kept in mind that the provision of Government services for meeting user requirements is subject to the budgetary process, including authorizations and appropriations by Congress, and priorities for allocations among programs by agencies.

2.2.1 Process

The requirements for an area or class of users are not absolutes. The process to determine requirements involves:

- Evaluation of the acceptable level of safety risks to the Government, user, and general public as a function of the service provided.
- Evaluation of the economic needs in terms of service needed to provide cost-effective benefits to commerce and the public at large. This involves a detailed study of the service desired measured against the benefits obtained.
- Evaluation of the total cost impact of any government decision on radionavigation system users.

This process leads to government selection of a system. The decision is driven primarily by considerations of safety and economic benefit.

2.2.2 User Factors

User factors requiring consideration are:

- Vehicle size and maneuverability.
- Regulated and unregulated traffic flow.
- User skill and workload.
- Processing and display requirements for navigation and positioning information.
- Environmental constraints; e.g., weather, terrain, or man-made obstructions.
- Operational constraints inherent to the system.
- Safety constraints.
- Economic benefits.

For most users, cost is generally the driving consideration. The price users are willing to pay for equipment is influenced by:

- Activity of the user; e.g., recreational boaters, air taxi, general aviation, mineral exploration, helicopters, commercial shipping, and positioning, surveying, and timing.
- Vehicle performance variables such as fuel consumption, operating costs, and cargo value.
- Cost/performance trade-offs of radionavigation equipment.

Thus, in the civil sector, evaluation of a navigation system against requirements involves more than a simple comparison of accuracy and equipment performance characteristics. These evaluations must involve the operational, technical, and cost elements discussed above. Performance requirements are defined within this framework.

2.3 Civil Air Radionavigation Requirements

Aircraft navigation is the process of piloting aircraft from one place to another and includes position determination, establishment of course and distance to the desired destination, and determination of deviation from the desired track. Requirements for navigational performance are dictated by the phase of flight and their relationship to terrain, to other aircraft, and to the air traffic control process. Aircraft navigation may be achieved through the use of visual procedures during Visual Flight Rules

(VFR) operations but requires navigation avionics when operating under Instrument Flight Rules (IFR) or above Flight Level (FL) 180 (18,000 ft).

Aircraft separation criteria, established by the FAA, take into account limitations of the navigational service available and, in some airspace, the Air Traffic Control (ATC) surveillance service. Aircraft separation criteria are influenced by the quality of navigational service, but are strongly affected by other factors as well. The criteria relative to separation require a high degree of confidence that an aircraft will remain within its assigned volume of airspace. The dimensions of the volume are determined, in part, by a stipulated probability that performance of the navigation system will not exceed a specified error.

Since navigation is but one function performed by the pilot, the workload for navigation in conjunction with communications, flight control, and engine monitoring must be small enough so that the pilot has time to adequately see and avoid other aircraft when operating using see-and-avoid rules.

The following are basic requirements for the aviation navigation systems. “Navigation system” means all of the elements necessary to provide navigation services to each phase of flight. While navigation systems are expected to be able to meet these requirements, implementation of specific capabilities is to be determined by the users and, where appropriate, regulatory authorities.

No single set of navigational and operational requirements, even though they meet the basic requirement for safety, can adequately address the many different combinations of operating conditions encountered in various parts of the world. Requirements applicable to the most exacting region may be considered extravagant when applied to others. In general,

a. The navigation system must be suitable for use in all aircraft types which may require the service without unduly limiting the performance characteristics or utility of those aircraft types; e.g., maneuverability and fuel economy.

b. The navigation system must be safe, reliable, and available; and appropriate elements must be capable of providing service over all the used airspace of the world, regardless of time, weather, terrain, and propagation anomalies.

c. The integrity of the navigation system, including the presentation of information in the cockpit, shall be near 100 percent and, to the extent feasible, should provide timely alarms in the event of failure, malfunction, or interruption.

d. The navigation system must recover from a temporary loss of signal without the need for complete resetting.

e. The navigation system must provide in itself maximum practicable protection against the possibility of input blunder, incorrect setting, or misinterpretation of output data.

f. The navigation system must provide adequate means for the pilot to check the accuracy of airborne equipment.

g. The navigation information provided by the systems must be free from unresolved ambiguities of operational significance.

h. Any source-referenced element of the total navigation systems shall be capable of providing operationally acceptable navigational information simultaneously and instantaneously to all aircraft which require it within the area of coverage.

i. In conjunction with other flight instruments, the navigation system must in all circumstances provide information to the pilot and aircraft systems for performance of the following functions:

- Continuous track deviation guidance.
- Continuous determination of distance along track.
- Continuous determination of position of aircraft.
- Position reporting.
- Manual or automatic flight.

j. The navigation system must be capable of being integrated into the overall ATC system.

k. The navigation system should be capable of integration with all phases of flight, including the precision approach and landing system. It should provide for transition from long-range (overwater) flight to short-range (domestic) flight with minimum impact on cockpit procedure/displays and workload.

l. The navigation system must permit the pilot to determine the position of the aircraft with an accuracy and frequency that will (a) ensure that the separation minima can be maintained at all times, (b) execute properly the required holding and approach patterns, and (c) maintain the aircraft within the area allotted to the procedures.

m. The navigation system must permit the establishment and the servicing of any practical defined system of routes for the appropriate phases of flight.

n. The system must have sufficient flexibility to permit changes to be made to the system of routes and siting of holding patterns without imposing unreasonable inconvenience or cost to the providers and the users of the system.

o. The navigation system must be capable of providing the information necessary to permit maximum utilization of airports and airspace.

p. The navigation system must be cost-effective to both the Government and the users.

q. The navigation system must employ equipment to minimize susceptibility to interference from adjacent radio-electronic equipment and shall not cause objectionable interference to any associated or adjacent radio-electronic equipment installation in aircraft or on the ground.

r. The navigation system must be free from signal fades or other propagation anomalies within the operating area.

s. The navigation system must be capable of furnishing reduced service to aircraft with limited or partially inoperative equipment.

t. The navigation system must be capable of being coupled with the aircraft flight control system to provide automatic tracking.

2.3.1 Navigation Signal Error Characteristics

The unique signal characteristics of a navigation system have a direct effect on determining minimum route widths. The distribution and rate of change, as well as magnitude of the errors, must be considered. Error distributions may contain both bias and random components. The bias component is generally easily compensated for when its characteristics are constant and known. For example, VOR radials can be flight-checked and the bias error reduced or eliminated through correction of the radial used on aeronautical charts.

The Loran-C and Omega seasonal and diurnal variations can also be compensated for by implementing correction algorithms in aircraft equipment logic and by publishing corrections periodically for use in air equipment.

The distribution of the random or unpredictable varying error component becomes the critical element to be considered in the design of navigation systems. The rate of change of the error within the distribution is also an important factor, especially when the system is used for approach and landing.

Errors varying at a very high frequency can be readily integrated or filtered out in the aircraft equipment. Errors occurring at a slower rate can be troublesome and result in disconcerting indications to the pilot. An example of one of these would be a "scalloped" VOR signal that causes the Course Deviation Indicator (CDI) to vary. If the pilot attempts to follow the CDI closely, the plane will start to "S" turn frequently. The maneuvering will cause unnecessary pilot workload and degrade pilot confidence in the navigation system. This indication can be further aggravated if navigation systems exhibit different error characteristics during different phases of flight or when the aircraft is maneuvering. The method of determining the total system error is affected by the navigation signal error characteristics. In most current systems the error components are ground system errors, airborne receiver errors, and flight technical errors. These errors are combined using the Root-Sum-Square (RSS) method. In analyzing new systems, it may be necessary to utilize alternative methods of combining errors, but each element must be properly considered.

In summary, the magnitude, nature, and distribution of errors as a function of time, terrain, aircraft type, aircraft maneuvers, and other factors must be considered. The evaluation of errors is a complex process, and the comparison of systems based upon a single error number will be misleading.

2.3.2 Current Aviation Navigation Requirements

The current aviation navigation requirements for all phases of flight are listed in Table 2-2.

En Route/Terminal Phase: The en route/terminal phase of air navigation (as defined in Section 2.1.1.A) includes the following subphases:

- Oceanic En Route
- Domestic En Route
- Terminal Area
- Remote Area

The general requirements in Section 2.3 are applicable to the en route/terminal phase of flight. In addition, to facilitate aircraft navigation in this phase, the system must be capable of being operationally integrated with the system used for approach and landing.

Federal Aviation Regulations (FAR) paragraphs 91.119 and 91.121 specify the vertical separation required below and above FL 290. The current separation requirement is 1,000 feet below FL 290, and 2,000 feet at and above FL 290. In order to justify the 1,000-foot vertical separation below FL 290, the RSS altitude keeping requirement is $\pm$350 feet (3 sigma). This error is comprised of $\pm$250 feet (3 sigma) aircraft altimetry system error, of which the altimeter error is limited to $\pm$125 feet by Technical Standard Order (TSO) C-10B below FL 290.

The minimum performance criteria currently established to meet requirements for the en route/terminal phase of flight are presented in the following sections.

A. Oceanic En Route

The system must provide navigational capability commensurate with the need in specific areas in order to permit safe navigation and the application of lateral separation criteria. An organized track system has been implemented in the North Atlantic to gain the benefit of optimum meteorological conditions. Since an independent surveillance system such as radar is not available, separation is maintained by procedural means (e.g., position reports and timing).

Table 2-2. Controlled Airspace Navigation Accuracy Requirements

<table>
<tr><th>PHASE</th><th colspan="2">SUB-PHASE</th><th>ALTITUDE FL/FT</th><th>TRAFFIC DENSITY</th><th>ROUTE WIDTH (nm)</th><th colspan="2">SOURCE ACCURACY CROSS -TRACK (95%, nm)</th><th>SYSTEM USE ACCURACY CROSS -TRACK (95%, nm)</th></tr>
<tr><td rowspan="5">EN ROUTE/ TERMINAL</td><td colspan="2">Oceanic</td><td>FL 275 to 400</td><td>Normal</td><td>60*</td><td colspan="2">12.4*</td><td>12.6*</td></tr>
<tr><td colspan="2" rowspan="3">Domestic</td><td rowspan="2">FL 180 TO 600</td><td>Low</td><td>16</td><td colspan="2">2.8</td><td>3.0</td></tr>
<tr><td>Normal</td><td>8</td><td colspan="2">2.8</td><td>3.0</td></tr>
<tr><td>500 FT to FL 180</td><td>High</td><td>8</td><td colspan="2">2.8</td><td>3.0</td></tr>
<tr><td colspan="2">Terminal</td><td>500 FT to FL 180</td><td>High</td><td>4</td><td colspan="2">1.7</td><td>2.0</td></tr>
<tr><td rowspan="7">APPROACH AND LANDING</td><td colspan="2">Nonprecision</td><td>250 to 3,000 FT</td><td>Normal</td><td>N/A</td><td colspan="2">0.3</td><td>0.6</td></tr>
<tr><td rowspan="6">Precision</td><td rowspan="2">CAT I</td><td rowspan="2">N/A</td><td rowspan="2">Normal</td><td rowspan="2">N/A</td><td>+/-17.1 **</td><td>+/-4.1 ***</td><td rowspan="2">N/A</td></tr>
<tr><td colspan="2">CAT I Decision Height Point ****</td></tr>
<tr><td rowspan="2">CAT II</td><td rowspan="2">N/A</td><td rowspan="2">Normal</td><td rowspan="2">N/A</td><td>+/-5.2 **</td><td>+/-1.7 ***</td><td rowspan="2">N/A</td></tr>
<tr><td colspan="2">CAT II Decision Height Point ****</td></tr>
<tr><td rowspan="2">CAT III</td><td rowspan="2">N/A</td><td rowspan="2">Normal</td><td rowspan="2">N/A</td><td>+/-4.1 **</td><td>+/- 0.6 ***</td><td rowspan="2">N/A</td></tr>
<tr><td colspan="2">At Runway Threshold ****</td></tr>
</table>

* *North AtlanticTrack System requirements.*
** *Lateral position accuracy in meters.*
*** *Vertical position accuracy in meters.*
**** *Assumes a 3^o glideslope and 8,000 ft. distance between runway threshold and localizer antenna.*

The lateral separation standard on the North Atlantic organized track system is 60 nm. The following system performance is required to achieve this separation:

1. The standard deviation of the lateral track errors shall be less than 6.3 nm, 1 sigma (12.6 nm, 2 sigma).
2. The proportion of the total flight time spent by aircraft 30 nm or more off track shall be less than 5.3×10^{-4}; i.e., less than 1 hour in 2,000 flight hours.
3. The proportion of the total flight time spent by aircraft between 50 and 70 nm off track shall be less than 1.3×10^{-4}; i.e., approximately 1 hour in 8,000 flight hours.

B. Domestic En Route

Domestic air routes are designed to provide airways that are as direct as practical between city pairs having significant air traffic. For VOR-defined routes, via navaids or radials, the protected airspace at FL 600 and below is 4 nm on each side of the route to a point 51 nm from the navaid, then increases in width on either side of the centerline at a 4.5 degree angle to a width of 10 nm on each side of the route at a distance of 130 nm from the navaid.

Current accuracy requirements for domestic en route navigation are based on the characteristics of the VOR/DME/VORTAC system and therefore relate to the angular characteristics of the VOR and TACAN azimuth systems and range characteristics of the distance measuring equipment (DME)/TACAN range systems. “System Use Accuracy,” as defined by ICAO, is the RSS of the ground station error contribution, the airborne receiver error, the display system contribution, and the Flight Technical Error (FTE). FTE is the contribution of the pilot (or autopilot) in using the presented information to control aircraft position. Error values on which the current system is based are as follows:

1. Azimuth Accuracy in Degrees:

Error Component	2 Sigma Deviation Values	Source
VOR Ground	$+1.4^{o}$	Semi-Automatic Flight Inspection (SAFI) System
VOR Air	$+3.0^{o}$	Equipment Manufacturer
Course Selection (CSE)	$+2.0^{o}$	FAA Tests
Flight Technical (FTE)	$+2.3^{o}$	FAA Tests
System Use Accuracy (95% Confidence)	$+4.5^{o}$	(RSS derived)

2. Range Accuracy

Where DME service is used, the system use accuracy is defined as $\pm$0.5 nm or 3 percent of distance (2 sigma), whichever is greater. This value covers all existing DME avionics. When DME is used with an RNAV system, the range accuracy must be at least $\pm$0.2 nm plus 1 percent of the distance (2 sigma).

3. Area Navigation (RNAV)

RNAV computation equipment provides latitude and longitude coordinate navigation capability. When RNAV equipment is used, an additional error contribution is specified and combined in RSS fashion with the basic VOR/DME system error. The additional maximum RNAV equipment error allowed, per FAA Advisory Circular AC 90-45A, is $\pm$0.5 nm. RNAV system performance and route design is based on the following error budget:

Error Component	**2 Sigma Deviation Values**	**Source**
VOR Ground	$+1.4^{o}$	SAFI
VOR Air	$+3.0^{o}$	Equipment Manufacturer and FAA Tests
DME Ground	+0.1 nm	SAFI

The VOR/DME and RNAV error values identified below result in 95 percent of the aircraft remaining within $\pm$4 nm of the airway centerline out to 51 nm from a VOR facility and within $\pm$4.5 degrees (originating at the VOR facility) of the airway centerline when beyond 51 nm from a VOR facility.

Error Component	**2 Sigma Deviation Values**	**Source**
DME Air	+0.2 nm + 1% of Range	Equipment Manufacturer*
FTE	+1.0 nm	FAA Tests**
CSE	$+2.0^{o}$	FAA Tests
RNAV System	+0.5 nm	Equipment Manufacturer and FAA Tests

*Only DME aircraft equipment with this accuracy or better is used.
**FTE -0.5 nm in the approach phase.

C. Terminal Area

Terminal routes provide transitions from the en route phase to the approach phase of flight. The accuracy capability of navigation systems using VOR/DME in terms of bearing and distance to the facility is defined in the same manner as described for en route navigation. However, the usually closer proximity to facilities provides greater effective system use accuracy since both VOR and FTE are angular in nature and are related to the distance to the facility. The DME distance error is also reduced, since it is proportional to distance from the facility, down to the minimum error capability. Thus the system use accuracy requirement is $\pm$2 nm (95 percent) within 25 nm of the facility, based on the RSS the combination of error elements.

D. Remote Areas

Remote areas are defined as regions which do not meet the requirements for installation of VOR/DME service or where it is impractical to install this system. These include offshore areas, mountainous areas, and a large portion of the state of Alaska. Thus the minimum route width varies and can be greater than $\pm$10 nm.

E. Operations Between Ground Level and 5,000 Feet Above Ground Level (AGL)

Operations between ground level and 5,000 feet AGL occur in offshore, mountainous, and high-density metropolitan areas as well as on domestic routes. For operations from U.S. coastline to offshore points, the following requirements must be met:

- Range from shore to 300 nm.
- Minimum en route altitude of 500 feet above sea level or above obstructions.
- Accuracy adequate to support routes $\pm$4 nm wide or narrower with 95 percent confidence.
- Minimum descent altitude to 100 feet in designated areas.

For helicopter operations over land, the following requirements must be met:

- Accuracy adequate to support $\pm$2 nm route widths in both en route and terminal areas with 95 percent confidence.
- Minimum en route altitudes of 1,200 feet AGL.
- Navigation signal coverage adequate to support approach procedures to minimums of 250 feet above obstruction altitudes at heliports and airports.

Approach/Landing Phase: This phase of flight is one of two types: (1) nonprecision approach, or (2) precision approach and landing.

The general requirements of Section 2.3 apply to the approach/landing phase. In addition, specific procedures and clearance zone requirements are specified in TERPS (United States Standard for Terminal Instrument Procedures, FAA Handbook 8260.3B).

Altimetry accuracy requirements are established in accordance with FAR 91.411 and are the same as those for the en route/terminal phase.

The minimum performance criteria currently established to meet requirements for the approach/landing phase of navigation vary between precision and nonprecision approaches.

A. Nonprecision Approach

Nonprecision approaches are based on any navigational system that meets the criteria established in TERPS. Minimum safe altitude, obstacle clearance area, visibility minimum, final approach segment area, etc., are all functions of the navigational accuracy available and other factors. The unique features of RNAV for nonprecision approaches are specified in FAA Advisory Circulars No. 90-45A, "Approval of Area Navigation Systems for Use in the U.S. National Airspace System;" No. 20-130, "Airworthiness Approval of Multi-Sensor Navigation Systems in U.S. National Airspace System (NAS) and Alaska;" 20-121A, "Airworthiness Approval of the Loran-C Navigation System for Use in U.S. National Airspace (NAS) and Alaska;" and TSO C129, "Airborne Supplemental Navigation Equipment Using the Global Positioning System."

The achieved capability for nonprecision approaches varies significantly, depending on the location of the navigational facility in relation to the fix location and type of navigational system used. Approximately 30 percent of the nonprecision approach fixes based on VOR in the U.S. achieve a cross track navigational accuracy of $\pm$100 meters (2 sigma) at the missed approach point (MAP). This accuracy is based upon the $\pm$4.5 degrees VOR system use accuracy and the MAP being less than 0.7 nm from the VOR facility.

Nonprecision RNAV approaches must satisfy their own criteria and are based on the obstacle clearance areas shown in Figure 2-1. The width of the intermediate approach trapezoid primary areas decreases from 4 nm (2 nm each side of the route centerline) at the end of the intermediate fix or waypoint displacement area to 2 nm (1 nm each side of the route centerline) at the final approach fix or waypoint. Primary obstacle clearance areas further narrow to the width of the runway waypoint fix displacement area at its furthest point. Secondary areas (not depicted) also extend upward and outward from the sides of the primary area.

The integrity time-to-alarm requirement for nonprecision approaches provides the pilot with either a warning or a removal of signal within 10 seconds of the occurrence of an out-of-tolerance condition.

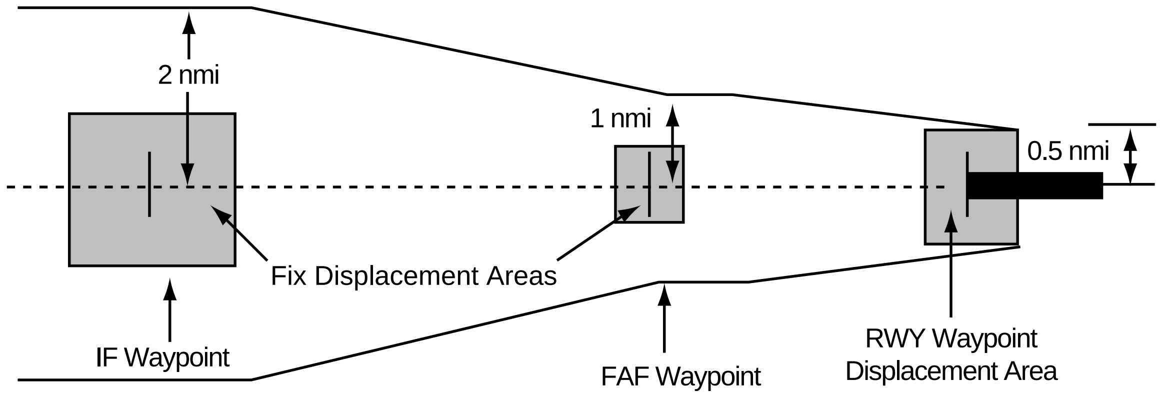

Figure 2-1. RNAV Nonprecision Approach Protected Areas

B. Precision Approach and Landing

Precision approach and landing radio aids provide vertical and horizontal guidance and position information. ILS and MLS are of this type. International agreements have been made to achieve an all-weather landing capability through an evolutionary process, reducing landing weather minima on a step-by-step basis as technical capabilities and operational knowledge permit. The performance objectives for the various landing categories are shown in Table 2-2.

The MLS and ILS system integrities, during precision approaches, warn the pilot of an out-of-tolerance condition by removing these signals from service. The response time for providing these warnings varies from six seconds for Category I to two seconds for Category II/III.

C. Current System Requirements Summary

The system use accuracy criteria to meet the current route requirements are summarized in Table 2-2. These route widths are based upon present capacities, separation requirements, and obstruction clearance requirements. Availability requirements are being developed.

2.3.3 Future Aviation Radionavigation Requirements

Future aviation navigation requirements will be based on new criteria using the concept of required navigation performance (RNP). This concept will be developed such that unified criteria will be established for airworthiness approval, ground equipment approval (if required), operating approval, establishment of operating minima and obstacle clearance assessment. Aviation requirements in the next edition of the FRP are expected to be expressed using this method.

Altimetry requirements for vertical separation of 1,000 feet, below FL 290, are not expected to change. Increased altimetry accuracy is needed at and above FL 290 to permit separation less than the current standard of 2,000 feet. The required future 3 sigma value of the aircraft altimetry system error has not been specified, but it must be accurate enough to support the introduction of 1,000-foot vertical separation at all flight levels.

En Route/Terminal Phase

A. Oceanic En Route

Separation specifications have been designed to allow a lateral separation of 60 nm. This was put into effect for certain areas of the North Atlantic in early 1981 and requires a lateral track error less than 12.6 nm (95 percent). More accurate and reliable aircraft position data will greatly contribute to reductions in lateral separation, resulting in greater flexibility and the ability to fly user-preferred routes.

B. Domestic En Route

At the present time, the number of VOR/DMEs is sufficient to allow most routes to have widths of $\pm$4 nm. This is possible as most VOR facilities are spaced less than 100 nm apart on the route. However, greater spacings are used in low traffic density areas, remote areas, and on most of the high-altitude route structure. Parts of the high-altitude route structure have a distance between VOR facilities resulting in route widths up to 20 nm.

Traffic increases are causing route capacity problems. More use of RNAV equipment will allow the implementation of random and parallel routes not possible with the use of current VOR/DME facilities. No increase in VOR/DME ground accuracy is required to meet the navigational requirements imposed by the air traffic levels estimated for the year 2000.

C. Terminal Area

The major change forecasted for the terminal area is the increased use of RNAV and time control to achieve optimum runway utilization and noise abatement procedures. Some current multi-DME RNAV avionics can provide cross track navigational accuracies better than $\pm$500 meters (2 sigma) in terminal areas using the current VOR/DME facilities. Similarly, GPS-based avionics deliver better accuracies and performance than VOR/DME in the terminal area.

D. Remote Areas

Many areas, such as Alaska, the Rocky Mountains and other mountainous areas, and some offshore locations, cannot be served easily or at all by VOR/DME. Presently, nondirectional beacons (NDB), Omega, and privately owned facilities such as

TACAN are being used in combination to meet the user navigational needs in these areas. GPS, Omega and Loran-C are being used as supplements to VOR/DME to meet these needs. The accuracy and coverage of these systems seem adequate to handle the traffic densities projected for the different areas.

Approach/Landing Phase

A. Nonprecision Approach

No changes are envisioned at this time to the nonprecision approach obstacle clearance areas.

B. Precision Approach and Landing

Future requirements for precision approaches are expected to be based on required navigation performance and the developing “tunnel concept.” These requirements will describe a 95 percent containment accuracy surface and a 10^{-7} outer containment surface. The associated accuracy requirements are depicted in Figure 2-2.

2.4 Civil Marine Radionavigation Requirements

The navigational requirements of a vessel depend upon its general type and size, the activity in which the ship is engaged (e.g., point-to-point transit, fishing) and the geographic region in which it operates (e.g., ocean, coastal), as well as other factors. Safety requirements for navigation performance are dictated by the physical constraints imposed by the environment and the vessel, and the need to avoid the hazards of collision, ramming, and grounding.

The above discussion of phases of marine navigation (Section 2.1.2) sets the framework for defining safety of navigation requirements. However, the economic and operational dimensions also need to be considered for the wide diversity of vessels that traverse the oceans and U.S. waters. For example, navigation accuracy (beyond that needed for safety) is particularly important to the economy of large seagoing ships having high hourly operating costs. For fishing and oil exploration vessels, the ability to locate precisely and return to productive or promising areas and at the same time avoid underwater obstructions or restricted areas provides important economic benefits. Search and Rescue (SAR) effectiveness is similarly dependent on accurate navigation in the vicinity of a maritime distress incident.

For system planning, the Government seeks to satisfy minimum safety requirements for each phase of navigation and to maximize the economic utility of the service for users. Since the vast majority of marine users are required to carry only minimal navigational equipment, and even then do so only if persuaded by individual cost/benefit analysis, this governmental policy helps to promote maritime safety through a simultaneous economic incentive.

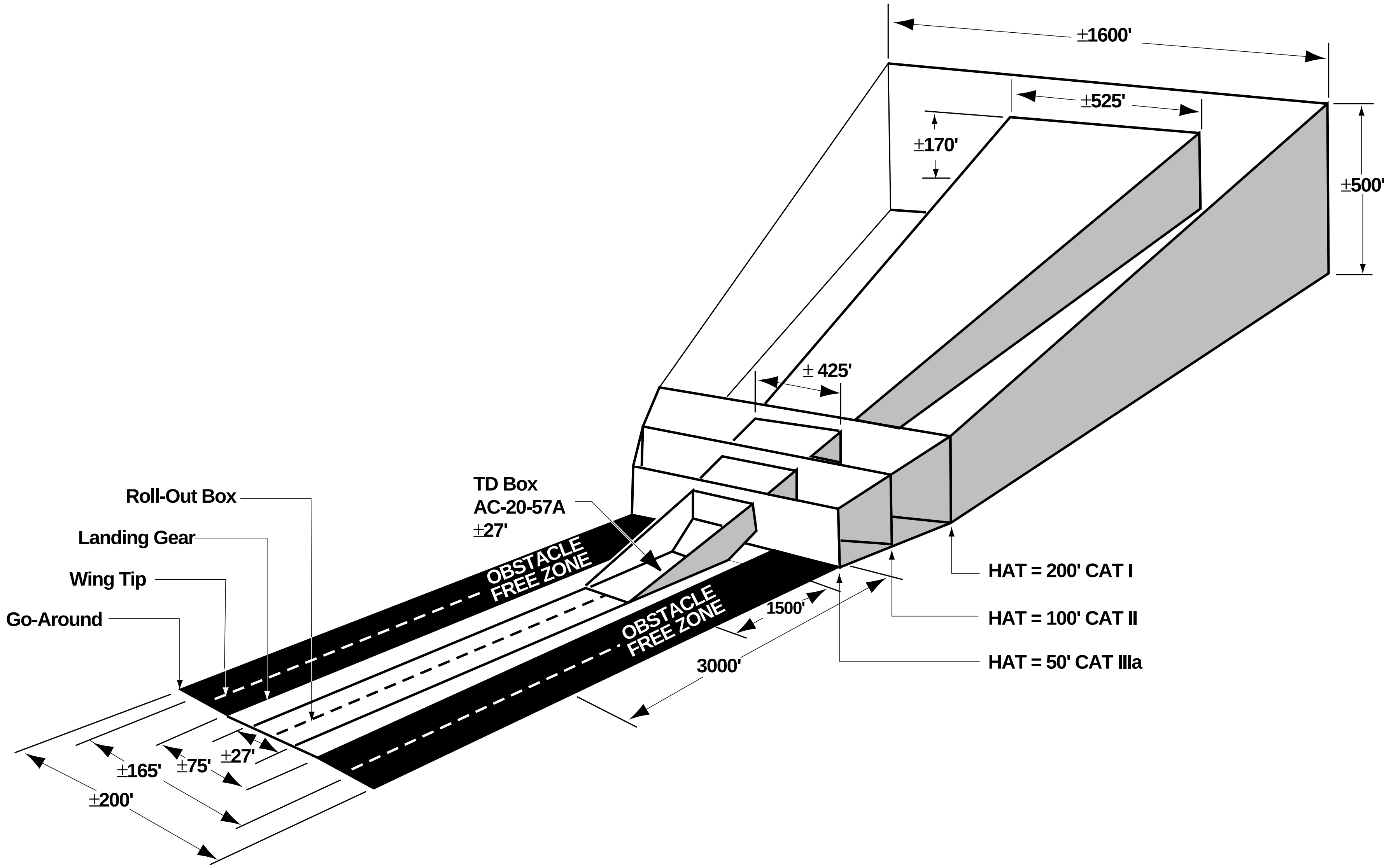

Figure 2-2. RNP for Precision Approach and Landing Tunnel

Tables 2-3, 2-4, and 2-5 identify system performance needed to satisfy maritime user requirements or to achieve special benefits in three of the four phases of marine navigation. The tables are divided into two categories. The upper half are those related to safety of navigation. The Government recognizes an obligation to satisfy these requirements for the overall national interest. The lower half are specialized requirements or characteristics needed to provide special benefits to discrete classes of maritime users (and additional public benefits which may accrue from services provided by users). The Government does not recognize an absolute commitment to satisfy these requirements, but does endeavor to meet them if their cost can be justified by benefits which are in the national interest. For the purpose of comparing the performance of systems, the requirements are categorized in terms of system performance characteristics representing the minimum performance considered necessary to satisfy the requirements or achieve special benefits.

2.4.1 Inland Waterway Phase

Very large amounts of commerce move on the U.S. inland waterway system, much of it in slow-moving, comparatively low-powered tug and barge combinations. Tows on the inland waterways, although comparatively shallow in draft, may be longer and wider than large seagoing ships which call at U.S. ports. Navigable channels used by this inland traffic are often narrower than the harbor access channels used by large ships. Restricted visibility and ice cover present problems in inland waterway navigation, as they do in harbor/harbor approach navigation. The long, ribbon-like nature of the typical inland waterway presents special problems to the prospective user of precise, land-based area navigation systems. Continual shifting of navigable channels in some unstable waters creates additional problems to the prospective user of any radionavigation system which provides position measurements in a fixed coordinate system.

Special waterways, such as the Saint Lawrence River and some Great Lakes passages, are well defined, but subject to frequent fog cover which requires ships to anchor. This imposes a severe economic penalty in addition to the safety issues. If a fog rolls in unexpectedly, a ship may need to proceed under hazardous conditions to an anchorage clear of the channel or risk stopping in a channel.

Requirements: Requirements based on the consideration of practically achievable performance and expected benefits have not been defined. However, Research, Engineering and Development (R,E&D) in harbor/harbor approach navigation is expected to produce results which will have some application to inland waterway navigation.

Minimum Performance Criteria: These criteria have not been determined. The R,E&D plans in Section 4 discuss the current and future efforts in the area of inland waterway navigation.

Table 2-3. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Harbor/Harbor Approach Phase

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
	ACCURACY (meters, 2drms)		COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE							
SAFETY OF NAVIGATION - LARGE SHIPS & TOWS	8-20***	-	US harbor & harbor approach	99.7%	**	6-10 seconds	Two	Unlimited	Resolvable with 99.9% confidence
SAFETY OF NAVIGATION - SMALLER SHIPS	8-20	8-20	US harbor & harbor approach	99.9%	**	***	Two	Unlimited	Resolvable with 99.9% confidence
RESOURCE EXPLORATION	1-5*	1-5m*	US harbor & harbor approach	99%	**	1 second	Two	Unlimited	Resolvable with 99.9% confidence

BENEFITS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
FISHING, RECREATIONAL & OTHER SMALL VESSELS	8-20	4-10	US harbor & harbor approach	99.7%	**	***	Two	Unlimited	Resolvable with 99.9% confidence

* Based on stated user need.

** Dependent upon mission time.

*** Varies from one harbor to another. Specific requirements are being reviewed by the Coast Guard.

Table 2-4. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Coastal Phase

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
	ACCURACY (meters, 2drms)		COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE							
SAFETY OF NAVIGATION - ALL SHIPS	0.25nm (460m)	-	US coastal waters	99.7%	**	2 minutes	Two	Unlimited	Resolvable with 99.9% confidence
SAFETY OF NAVIGATION - RECREATION BOATS & OTHER SMALLER VESSELS	0.25nm-2nm (460-3,700m)	-	US coastal waters	99.	**	5 minutes	Two	Unlimited	Resolvable with 99.9% confidence

BENEFITS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
COMMERCIAL FISHING (INCLUDING COMMERCIAL SPORT FISHING)	0.25nm (460m)	50-600 ft (15-180m)	US coastal/ fisheries areas	99%	**	1 minute	Two	Unlimited	
RESOURCE EXPLORATION	1.0-100m*	1.0-100m*	US coastal areas	99%	**	1 second	Two	Unlimited	
SEARCH OPERATIONS, LAW ENFORCEMENT	0.25nm (460m)	300-600 ft (90-180m)	US coastal/ fisheries areas	99.7%	**	1 minute	Two	Unlimited	
RECREATIONAL SPORTS FISHING	0.25nm (460m)	100-600 ft (30-180m)	US coastal areas	99%	**	5 minutes	Two	Unlimited	Resolvable with 99.9% confidence

* Based on stated user need.
** Dependent upon mission time.

Table 2-5. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Ocean Phase

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS									
	ACCURACY (2 drms)			COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE	RELATIVE							
SAFETY OF NAVIGATION - ALL CRAFT	2-4nm (3.7-7.4km) minimum 1-2nm (1.8-3.7km) desirable	-	-	Worldwide	99% fix at least every 12 hours	**	15 minutes or less desired; 2 hours maximum	Two	Unlimited	Resolvable with 99.9% confidence

BENEFITS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS									
LARGE SHIPS MAXIMUM EFFICIENCY	0.1-0.25nm* (185-460m)	-	-	Worldwide, except polar regions	99%	**	5 minutes	Two	Unlimited	Resolvable with 99.9% confidence
RESOURCE EXPLORATION	10-100m*	10-100m*	-	Worldwide	99%	**	1 minute	Two	Unlimited	Resolvable with 99.9% confidence
SEARCH OPERATIONS	0.1-0.25nm (460m)	0.25nm	185m	National maritime SAR regions	99%	**	1 minute	Two	Unlimited	Resolvable with 99.9% confidence

* Based on stated user need.
** Dependent upon mission time.

2.4.2 Harbor/Harbor Approach Phase (HHA)

The pilot of a vessel in restricted waters must direct its movement with great accuracy and precision to avoid grounding in shallow water, hitting submerged/partially submerged rocks, and colliding with other craft in congested waterways. Unable to turn around, and severely limited in the ability to stop to resolve a navigational problem, the pilot of a large vessel (or a tow boat and barge combination) may find it necessary to hold the total error in navigation within limits measured in a few feet while navigating in this environment. It would appear that a major step in maximizing the effectiveness of radionavigation systems in the harbor/harbor approach environment is to present the position information on some form of electronic display. This would provide a ship's captain, pilot, or navigator a continual reference, as opposed to plotting "outdated" fixes on a chart to show the recent past. It is also recognized that the role of the existing radionavigation system decreases in this harbor/harbor approach environment, while the role of visual aids and radar escalates.

Requirements: To navigate safely, the pilot needs highly accurate verification of position almost continuously, together with information depicting any tendency for the vessel to deviate from its intended track and a nearly continuous and instantaneous indication of the direction in which the pilot should steer. Table 2-3 was developed to present estimates of these requirements. To effectively utilize the requirements stated in the table, however, a user must be able to relate the data to immediate positioning needs. This is not practical if one attempts to plot fixes on a chart in the traditional way. To utilize radionavigation information that is presented at less than 10-second intervals on a moving vessel, some form of an automatic display is required. Technology is available which presents radionavigation information along with other data.

Minimum Performance Criteria: The radionavigation system accuracy required to provide useful information in the harbor/harbor approach phase of marine navigation varies from harbor to harbor, as well as with the size of the vessel. In the more restricted channels, accuracy in the range of 8 to 20 meters (2 drms) relative to the channel centerline may be required for the largest vessels. A need exists to more accurately determine these radionavigation requirements for various-sized vessels while operating in such restricted confines. Radionavigation user conferences have indicated that for many mariners, the radionavigation system becomes a secondary tool when entering the harbor/harbor approach environment.

Continuing efforts are being directed toward verifying user requirements and desires for radionavigation systems in the harbor/harbor approach environment.

2.4.3 Coastal Phase

There is need for continuous, all-weather radionavigation service in the coastal area to provide, at the least, the position fixing accuracy to satisfy minimum safety requirements for general navigation. These requirements are delineated in Table 2-4. Furthermore, the total navigational service in the coastal area must provide service of useful quality and be within the economic reach of all classes of mariners. It should be sufficient to assure that no boat or ship need be lost or endangered, or that the environment and public safety not be threatened, because a vessel could not navigate safely with reasonable economic efficiency.

Requirements: Requirements on the accuracy of position fixing for safety purposes in the coastal phase are established by:

- The need for larger vessels to navigate within the designated one-way traffic lanes at the approaches to many major ports, in fairways established through offshore oil fields, and at safe distances from shallow water.
- The need to define accurately, for purposes of observing and enforcing U.S. laws and international agreements, the boundaries of the Fishery Conservation Zone, the U.S. Customs Zone, and the territorial waters of the U.S.

Minimum Performance Criteria: Government studies have established that a navigation system providing a capability to fix position to an accuracy of 0.25 nm will satisfy the minimum safety requirements if a fix can be obtained at least every 15 minutes. As a secondary economic factor, it is required that relatively higher repeatable accuracy be recognized as a major advantage in the consideration of alternative candidate radionavigation systems for the coastal area. As indicated in Table 2-4, these requirements may be relaxed slightly for the recreational boat and other small vessels.

In such activities as marine scientific research, hydrographic surveying, commercial fishing, and petroleum or mineral exploration, as well as in Navy operations, there may be a need to establish position in the coastal area with much higher accuracy than that needed for safety of general navigation. In many of these special operations which require highly accurate positions, the use of radiodetermination would be classified as radiolocation rather than radionavigation. As shown in Table 2-4, the most rigid requirement of any of this general group of special operations is for seismic surveying with a repeatable accuracy on the order of 1 to 100 meters (2 drms), and a fix rate of once per second for most applications.

2.4.4 Ocean Phase

The requirements for safety of navigation in the ocean phase for all ships are given in Table 2-5. These requirements must provide the Master with a capability to avoid hazards in the ocean (e.g., small islands, reefs) and to plan correctly the approach to land or restricted waters. For many operational purposes, repeatability is necessary to locate and return safely to the vicinity of a maritime distress, as well as for special activities such as hydrography, research, etc. Economic efficiency in safe transit of open ocean areas depends upon the continuous availability of accurate position fixes to enable the vessel to follow the shortest safe route with precision, minimizing transit time.

***Requirements**:* For safe general navigation under normal circumstances, the requirements for the accuracy and frequency of position fixing on the high seas are not very strict. As a minimum, these requirements include a predictable accuracy of 2 to 4 nm coupled with a maximum fix interval of 2 hours or less. These minimum requirements would permit reasonably safe oceanic navigation, provided that the navigator understands and makes allowances for the probable error in navigation, and provided that more accurate navigational service is available as land is approached. While these minimum requirements would permit all vessels to navigate with relative safety on the high seas, more desirable requirements would be predictable accuracy of 1 to 2 nm and a fix interval of 15 minutes or less. The navigation signal should be available 95 percent of the time. Further, in any 12-hour period, the probability of obtaining a fix from the system should be at least 99 percent.

Larger recreational craft and smaller commercial fishing vessels which sail beyond the range of coastal navigation systems require, for a reasonable level of safety, some means of establishing their position reliably at intervals of a few hours at most. Even more so than with larger ships, this capability is particularly important in time of emergency or distress. Many operators of these craft, however, will accept the risk of ocean sailing without reliable radionavigation unless that capability is available at relatively low cost.

***Minimum Performance Criteria**:* Economic efficiency in transoceanic transportation, special maritime activities and safety in emergency situations require or benefit from navigational accuracy higher than that needed for safety in routine, point-to-point ocean voyages. These requirements are summarized in Table 2-5. The predictable accuracy requirements may be as stringent as 10 meters for special maritime activities, and may range to 0.25 nm for large, economically efficient vessels, including search operations. Search operations must also have a repeatable accuracy of at least 0.25 nm. As indicated in Table 2-5, the required fix interval may range from as low as once per 5 minutes to as high as once per minute. Signal availability must be at least 95 percent and approach 99 percent for all users.

2.4.5 Future Marine Radionavigation Requirements

The marine radionavigation requirements presented in the preceding discussions and tables are based on a combination of requirements studies, user inputs, and estimates. However, they are the product of current technology and operating practices, and are therefore subject to revision as technologies and operating techniques evolve. The principal factors which will impact future requirements are safety, economics, energy conservation, environment, and evolving technologies.

Special radionavigation requirements may arise from new environmental laws and regulations designed to reduce marine vessel casualty events. Also, the role of commercial ships in military sealift missions may require additional navigation systems capabilities.

Safety:

A. Increased Risk from Collision, Grounding, and Ramming

Hazardous cargoes (petroleum, chemicals, etc.) are carried in great volumes in U.S. coastal and inland waterways. Additionally, the ever increasing volume of other shipping and the increasing numbers of smaller vessels act to constantly increase the risk of collision, grounding, and ramming. Economic constraints also cause vessels to be operated in a manner which, although not unsafe, places more stringent demands on all navigation systems.

B. Increased Size and Decreased Maneuverability of Marine Vessels

The desire to minimize costs and to capture economies of scale in marine transportation have led to design and construction of larger vessels and unitized tug/barge combinations, both of which are relatively less powerful and maneuverable than their predecessors. Consequently, improved navigational performance is needed.

C. Greater Need for Traffic Management/Navigational Surveillance Integration

The foregoing trends underlie the importance of continued governmental involvement in marine vessel traffic management to assure reasonable safety in U.S. waters. Radionavigation systems may become an essential component of traffic management systems. Differential GPS is expected to play an increasingly important role in such areas as VTS.

Economics:

A. Greater Congestion in Inland Waterways and Harbor/Harbor Approaches

In addition to the safety penalty implicit in greater congestion in restricted waterways, there are economic disadvantages if shore facilities are not used effectively and efficiently. Accurate radionavigation systems can contribute to better productivity and decreased delay in transit.

B. All Weather Operations

Low visibility and ice-covered waters presently impede full use of the marine transportation mode. Evolving radionavigation systems may eventually alleviate the impact of these restrictions.

Environment*:* As onshore energy supplies are depleted, resource exploration and exploitation will move further offshore to the U.S. outer continental shelf and to harsher and more technically demanding environments. In addition, more intensive U.S. fishing activity is anticipated as the result of legislative initiatives and the creation of the U.S. Fishery Conservation Zone. In summary, both sets of activities may generate demands for navigational services of higher quality and for broadened geographic coverage in order to allow environmentally sound development of resources.

Energy Conservation*:* The need to conserve energy resources and to reduce costs provides powerful incentives for increased transportation efficiency, some of which could come from better navigation systems.

2.5 Civil Land Radionavigation User Requirements

Requirements for use of radionavigation systems for land vehicle navigation are being developed. Many civil land applications for radionavigation systems are currently being investigated, and vehicular radionavigation systems are being tested by state and Federal government agencies and private industry. Radionavigation systems for automatic vehicle location, automated vehicle monitoring, and automated dispatch have already been fielded. Also, several tens of thousands of radionavigation receivers are estimated to be in use by land vehicles in the U.S. in general transportation, emergency services, and the transportation of hazardous materials. Many of these receivers are installed on trucks that engage in interstate commerce.

A variety of space and terrestrial radio communications systems is used to communicate between the vehicles and the control or dispatch sites. Vehicle onboard status of system and fuel consumption to determine allocation of fuel taxes are among the types of information that can be communicated along with position.

ITS operational tests are continuing and it is clear that large scale deployment will include a number of navigation mechanisms and they will most likely be shared with other systems and services. For example, several ITS operational tests use GPS, which is already being shared with numerous other systems and communities, along with radiobeacon systems and other radiolocation systems. Such an approach for sharing brings benefits of more efficient use of the scarce radio frequency spectrum as well as reduction of capital cost of infrastructure and related operations, administration and maintenance costs.

While civil land applications for radionavigation systems appear to be concentrated in the transportation community, electronic chart development, receiver miniaturization, and cost reduction are leading to development of portable land navigators for the camper or backwoods sports enthusiast.

There is also considerable interest in using DGPS for various surveying functions.

Requirements: The navigation accuracy, availability, and integrity requirements of land modes of transportation as well as security requirements associated with radionavigation systems (including continuity of service) have been documented in the December 1993 *Report of the Joint DOD/DOT Task Force, The Global Positioning System: Management and Operation of a Dual Use System.* Highway requirements contained in the document are in the process of being validated under DOT contract. The accuracy requirements listed in Table 2-6 will be reviewed for reasonableness and applicability to the ITS program.

Table 2-6. Land Transportation Positioning/Navigation System Accuracy Requirements

Highways:	**Meters**
Navigation and route guidance	5-20
Automated vehicle monitoring	30
Automated vehicle identification	30
Public safety	10
Resource management	30
Accident or emergency response	30
Collision avoidance	1
Geophysical survey	5
Geodetic control	Submeter
Rail:	**Meters**
Position location	10-30
Train control	1
Transit:	**Meters**
Vehicle command and control	30-50
Automated voice bus stop annunciation	25-30
Emergency response	75-100
Data collection	25-35

A special case exists for the railroads, which are privately owned with the individual companies maintaining their right-of-ways, terminals, and rail equipment. While the railroads have not adopted GPS for traffic management or train control, they have conducted studies identifying the GPS augmentation criteria needed to support their operations. Those criteria will be included in requirements validation studies.

Integrity requirements for ITS functions are dependent on resolution of final system architecture issues, which are under study at this time. Values will probably range between 1 and 15 seconds, depending on the function. GPS will most likely not be the sole source of positioning data for collision avoidance systems, since the distance separations needed are in the order of meters. GPS may be used for speed and direction checking, reducing integrity requirements to the same range as for other ITS functions.

Integrity needs for rail use are 5 seconds for most functions. Those for transit are under study and are not available at this time. Availability for all functions, highways, transit and rail, is estimated as 99.7 percent.

While the Government has no statutory responsibility to provide radionavigation services for land radionavigation applications or for non-navigation uses, their existence and requirements are recognized in the Federal radionavigation systems planning process. Accordingly, the Government will attempt to accommodate the requirements of such users.

2.6 Requirements for Surveying, Timing, and Other Applications

Use of radionavigation systems for applications other than navigation is well-established in some fields and is rapidly increasing. While there may be many diverse uses, the majority fall into the following categories:

- Radiolocation: Using radionavigation systems signals for surveying and site registration; noting the location of a place or event for record purposes, or returning to it at a later time.

- Time/Frequency Dissemination: Using radionavigation system signals to accurately time nonassociated electronic systems.

- Meteorological Applications: Using radionavigation signals to support meteorological operations; namely, to track balloon-borne weather radiosondes and dropwindsondes released from weather reconnaissance aircraft.

- Tracking Applications: Tracking of goods for regulatory or commercial purposes.

Many non-navigation uses for radionavigation systems have developed over the years. Previous government studies and inputs from users had given a preliminary indication of such usage, and the extent of these non-navigation uses was emphasized at the FRP user conferences and Federal interagency meetings. These uses include wildlife migratory studies, forestry conservation, communications and power network timing systems, and site registration systems. Requirements for surveying, timing, and other uses are listed in Table 2-7.

Table 2-7. Requirements for Land Use, Surveying, Timing and Other Applications

Surveying

TASK	MINIMUM PERFORMANCE CRITERIA								Remarks
	Accuracy - 1 Sigma				Coverage %	Availability %	Interval		
	Position						Measurement Recording (seconds)	Solution Fix	
	Absolute (m)		Relative (cm)						
	Horizontal	Vertical	Horizontal	Vertical					
STATIC SURVEY	0.3	0.5	1.0	2.0	99	99	5	30 min.	0 - 25 km
GEODETIC SURVEY	0.1	0.2	1.0	2.0	99	99	5	4 hrs.	0 - 6000 km
RAPID SURVEY	0.3	0.5	2.0	5.0	99	99	1	5 min.	0 - 20 km
"ON THE FLY" KINEMATIC SURVEY	0.3	0.5	2.0	5.0	99	99	0.1 - 1.0	0.1 - 1.0 sec.	0 - 20 km Real Time

Timing and Other Applications

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
	ACCURACY (2 drms)			COVERAGE	AVAILABILITY	FIX INTERVAL	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE	RELATIVE						
COMMUNICATIONS NETWORK SYNCHRONIZATION	-	1 part in 10 (freq)*	-	Nationwide	99.7%	Continuous	N/A	Unlimited	N/A
SCIENTIFIC COMMUNITY	-	1 part in 10 (freq)	-	Worldwide	99.7%	Continuous	N/A	Unlimited	N/A
METEOROLOGY	Velocity 1m/sec	-	-	-	TBD	TBD	TBD	-	TBD
POWER NETWORK SYNCHRONIZATION	-	1ms**	-	North America	99.7%	1 second	Two	Unlimited	Resolvable with 99.9% confidence

* Proposed ITU Standard based on American Telephone and Telegraph "Stratum 1 Requirement".

** At any substation. 8ms (1/2 cycle) systemwide.

In addition to its space and aeronautics applications, NASA has requirements for the use of GPS in the monitoring of earth crystal dynamics. NASA sponsored the development of the International GPS Service (IGS) for Geodynamics and operates the data collection and analysis facilities which provide data products for use in a number of international geodynamic research efforts.

2.6.1 Geodesy and Surveying

The geodetic survey community has been an important user of radionavigation signals since 1957.

Although this community of users has historically concentrated on determining the geodetic coordinates of a survey geodetic monument, it has gone well beyond that -particularly with the advent of GPS. Today the geodetic user of radionavigation signals might be interested in the trajectory of an aircraft for a photogrammetric or gravimetric mission or in the precise trajectory of a satellite such as TOPEX/POSEIDON. The hydrographic surveyor might have a few-centimeter positioning requirement and a meter-level navigation requirement.

Since 1980, the geodetic surveyor has used the GPS carrier phase signals, both L1 and L2, to measure baseline vectors to the centimeter-level of accuracy and occasionally to the millimeter level. Today, surveyors routinely measure 5, 50, 500, and 5000 km baselines to centimeter accuracy in all components. The geodetic community has carried out considerable research and development and has developed models and methods that both the navigation and geodetic communities routinely use. As an example, the geodetic survey community developed the kinematic GPS survey methods which have quickly been adopted for precision navigation and positioning by the navigation community.

GPS is also increasingly used in the development of geographic information systems (GIS).

2.6.2 Timing/Frequency Offset Applications

There are currently no definitive statements of the requirements for timing and frequency offset applications. One national telephone company uses Loran-C and GPS extensively for communication network synchronization. It is estimated that a worldwide GPS ground network may be able to provide clock synchronization to better than one nanosecond and relative determination to one part in 10^{14}. These clock calibrations will be useful for deep space tracking and at astrophysical observatories. Several power companies are experimenting with GPS for measuring phase differences between major power transmission stations and substations, for event recording, for post-disturbance analysis, and for measuring the relative frequency of power systems.

2.6.3 *Meteorological Applications*

It is estimated that the international meteorological community launches several hundred thousand weather radiosondes and dropwindsondes a year worldwide to measure such atmospheric parameters as pressure, temperature, humidity, and wind speed and direction. Current technology uses Omega and Loran-C radionavigation signals to track the airborne instrument package and to measure wind speed and direction; however, research and development in the use of GPS is being pursued.

2.7 Space Radionavigation Requirements

Several programs conducted or supported by NASA are evaluating GPS for spacecraft position determination. TOPEX/POSEIDON, launched on August 10, 1992, is using a high-accuracy dual-band GPS flight receiver on an experimental basis. Based on successful experiments conducted on the Space Shuttle and on the TOPEX/POSEIDON and EUVE instrumented satellites, NASA is planning to implement GPS as an operational system on many future missions.

Planned and proposed future NASA spacecraft will require continued use of GPS.

- The International Space Station (ISS) is being designed to implement GPS for navigation, attitude determination, and Universal Time distribution. GPS will support onboard ISS system control functions as well as various experimenter data capture processes.

- The Space Shuttle will implement GPS for all three mission phases by 1998. GPS has been flight tested on various Shuttle missions and studies are being conducted to determine the extent of future cost savings that can be realized by replacing current ground facility functions with the automatic onboard GPS support.

- Two small satellite programs recently initiated by NASA to explore low cost access to space will implement GPS for navigation, time, and attitude determination functions. The use of low cost onboard GPS receivers for these basic functions may become a significant factor in providing inexpensive access to space for both future NASA and commercial small satellite projects.

- Where scientific data position accuracy is required with precision greater than that readily available from the GPS receiver onboard a spacecraft, a refinement of post-pass orbit data will be used. NASA has developed post-pass orbit data processing techniques using GPS on the TOPEX/POSEIDON satellite that provides accuracy at the 5 cm level. In order to accomplish this, some internal receiver parameters must be available for downlink with the science data.

- GPS tracking is being used by the NASA Deep Space Network (DSN) to improve knowledge of the Earth's pole position and speed of rotation. The use of GPS for this purpose is making a significant reduction in demand for measurements with deep space antennas. The centimeter level accuracy available with GPS tracking for geocentric correction to deep-space antenna coordinates is significantly improving the deep-space tracking error budget.

The use of GPS for space applications fall into two basic categories:

1. Onboard spacecraft vehicle navigation support where GPS will be used in near real-time applications for navigation and attitude determination. In this role, onboard navigation and attitude accuracy requirements are:

   - Three-dimensional position error not to exceed 20 m (1 sigma).
   - Three-dimensional velocity error not to exceed 0.1 m/sec (1 sigma).
   - Attitude determination error not to exceed 0.1 degree in each axis (1 sigma).
   - Clock offset error between coordinated universal time (UTC) and onboard receiver time not to exceed 1 microsecond (1 sigma).

2. Scientific data analysis support where GPS will be used to accurately locate instrument position in space when measurements are taken. Current accuracy requirements are to determine three dimensional position within 5 cm. However, more accurate positioning in the 1 to 2 cm range may be required in the future for some earth observation instruments. Ground-based post-pass processing techniques are being used today to achieve 5 cm accuracy for the TOPEX/POSEIDON spacecraft instruments and NASA is continuing to refine this technique to realize the higher accuracy levels in the future.

2.8 Military Radionavigation Requirements

Military forces must be prepared to conduct operations anywhere in the world, in the air, on and under the sea, on land, and in space. During peacetime, military platforms must conform to applicable national and international rules in controlled airspace, on the high seas, and in coastal areas. Military planning must also consider operations in hostile environments.

2.8.1 General Requirements

Military navigation systems should have the following characteristics:

- Worldwide coverage.

- User-passivity.
- Capability of denying use to the enemy.
- Support of unlimited number of users.
- Resistance to spoofing (imitative navigational signal deceptions), interference, jamming, and intrusion.
- Resistance to natural disturbances and hostile attacks.
- Effectiveness of real-time response.
- Availability for combined military operations with allies.
- Freedom from frequency allocation problems.
- Use of common grid for all users.
- Position accuracy that is not degraded by changes in altitude for air and land forces or by time of year or time of day.
- Accuracy when the user is in high “G” or other violent maneuvers.
- Maintenance by operating level personnel.
- Continuous availability for fix information.
- Non-dependence on externally generated signals.

The ideal military positioning/navigation system should be totally self-contained so that military platforms are capable of performing all missions without reliance on information from outside sources. No single system or combination of systems currently in existence meets all of the approved military navigation requirements. No known system can provide a common grid for all users and at the same time be passive, self-contained, and yield the worldwide accuracies required. The nature of military operations requires that essential navigation services be available, with the highest possible confidence that these services will equal or exceed mission requirements. This, among other considerations, necessitates a variety of navigational techniques and redundant installations on the various weapon system platforms for military operations. Currently, the DOD is unable to conduct some military missions with the precision and accuracy demanded without some aid from external radionavigation systems. However, there has been significant progress in the development of reliable self-contained systems (inertial systems, Doppler systems, geomagnetic navigation, and terrain/bottom contour matching).

While the survivability of any radionavigation system is scenario-dependent, in almost any scenario the GPS is considered more survivable than other systems because:

- Moving transmitters in space are less vulnerable than ground-based transmitters.
- Spread spectrum transmission techniques protect against jamming.
- Anti-spoofing is available.
- Transmitters are hardened against electromagnetic pulse (EMP).

Loran-C coverage is limited when viewed from a worldwide perspective, and six of the eight Omega transmitters are located in areas not controlled by the United States.

While reliance on a single POS/NAV system is unwise, redundant or backup systems for military operations should not be more vulnerable, less-capable external systems. Rather, DOD must invest in reliable, accurate, self-contained systems that are uniquely tailored to match platform mission requirements. Therefore, the DOD POS/NAV architecture will be based upon GPS, which provides accurate worldwide positioning, velocity and time, backed by modern, accurate, and dependable self-contained systems.

2.8.2 Service Requirements

The CJCS MNP provides specific DOD requirements for navigation, positioning, and timing accuracy organized by primary missions and functions with specifically related accuracy requirements. These requirements are used for information and guidance in the development and procurement of military navigation systems.